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Summary

The degraded visual information when hovering with Night Vision Goggles may induce drift that is not noticed by the pilot. We tested the possibilities of counteracting these effects by using a tactile torso display. The display consisted of 64 vibro-tactile elements and presented information on the desired direction of motion only (simple version), or also included information on the current motion direction (complex version). The participants flew in a fixed-base helicopter simulator with either full vision or with simulated night vision goggles. The results showed performance improvement for both tactile display variants compared to hovering without a tactile display. This improvement was present in the NVG conditions (mean reduction of the position error of 22% in the horizontal direction and of 41% in the vertical direction), but also in the full vision condition (mean reductions of 32 and 63%, respectively). Also, performance with a tactile display is less affected by the introduction of a secondary (cognitive) task than performance without a tactile display. The complex variant of the tactile torso display tends to be less effective than the simple variant. We hypothesize that this effect may be due to what we call "*tactile clutter*".

This simulator study proves the potential of intuitive tactile torso displays in reducing drift during hover. The display is so effective that it even results in performance improvement in full vision conditions. Also, the results prove that tactile displays can be applied in fast man-in-the-loop tasks. Finally, advanced tactile displays that are able to present more complex stimuli open up new possibilities of information presentation, but may also introduce tactile clutter.

Introduction

Tactile torso displays consist of numerous vibrators attached to the torso in a matrix arrangement. They convey information by presenting localized vibrations to the torso. Since these stimuli are directly mapped to the body coordinates, tactile displays are able to present spatial information in an intuitive way (Gilliland & Schlegel, 1994; Wood, 1998; Schrope, 2001; Van Erp, 2001a; Van Veen & Van Erp, 2001). This 'tap-on-the-shoulder' principle goes for locations (left is left, and right is right), but also for motion (forward is forward, and backward is backward). The potential of tactile displays as a countermeasure for reducing Spatial Disorientation has already been shown (Raj, Suri, Braithwaite & Rupert, 1998). The initial applications were based on relative simple technologies, and were restricted to activating single locations. Recent developments in the field of tactile torso displays allow to present much more complex spatio-temporal patterns, including motion and ensembles of stimuli (Van Erp & Van Veen, 2001).

We employed an advanced tactile torso display to counteract one of the problems that arise when flying with Night Vision Goggles (NVGs). The reduced visual information in this situation (quantitatively as well as qualitatively) may result in degraded motion perception. As a result, a rotary wing aircraft may drift substantially without the pilot detecting motion or a changed position. The tactile torso display in the current study consisted of 64 elements and was able to stimulate single locations as well as (apparent) motion.

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Objectives and hypotheses

The first objective of the present study is to investigate whether a tactile torso display can help to compensate for degraded visual information. We investigate the effects on performance and on mental effort. Therefore, we had a complicated design. First, we compared full vision and NVG vision. Our expectation was that the tactile display would improve the performance when flying with NVGs, but had no or only a small effect under full vision. Besides the day/night vision manipulation, we also manipulated the visual cues in the environment. Again, we expect a larger positive effect of the tactile displays with a sparse environment compared to a rich visual environment. Finally, we manipulated the (cognitive) workload by adding a secondary task (Continuous Memory Task). This was done to investigate the claim that tactile displays are 'intuitive', which implies low level information processing. We expected therefore, that the presence of a tactile display would make performance less affected by cognitive load.

Design of the tactile codes

At present, there is no such thing as a set of guidelines to develop tactile torso displays, partly because of the rapid but recent development of hardware and concepts. We will discuss some critical factors here. A real methodology must be developed before tactile displays can be systematically and consistently designed.

Besides the usual Human Factors issues (e.g., consistency and robustness), some specific issues are important for tactile displays. Van Erp and Van den Dobbelsteen (1998) give a more complete overview. For the present application, in which location and timing are the primary parameters, the following issues are important:

1 *Ecological meaning*. An ecological or intuitive display is a display that presents information in such a way that it is processed directly and sheer effortless. This is potentially a strong point of tactile torso displays. Recent research showed that spatial information is easily interpreted. Main reason is that the display is directly mapped onto the body coordinates. This holds for static points, but also for motion (forward is forward and backward is backward). The use of motion has not been extensively investigated yet. An optimal design employs these intuitive properties.

2. *The pace of presentation*. A tactile display will not be able to present large amounts of information in parallel like a visual display can. The resolution of tactile displays is too small, and the occurrence of spatio-temporal interaction may hamper perception (see also point 4). This means that messages have to be presented serially and that the required duration can be an obstructing factor (Van Erp, 2001b).

3. *Resolution*. Even with up to 100 elements, the resolution of the display is limited. This means that locations are 'rounded' to the nearest element. Especially when presenting patterns (e.g., lines), this may be important. A straight line on a low resolution display may not be straight at all. Also, aliasing effects can occur. Possible counter measures are the application of perceptual illusions (such as apparent position or the "tactile rabbit"; Geldard & Sherrick, 1972), or the preprogramming of specific spatial patterns (e.g., tilted lines). The latter means that the elements in the display will no longer be ordered along a regular matrix pattern.

4. *Interference*. The spatio-temporal integration of two or more signals may result in the occurrence of a completely new percept. This may happen with parallel as well as with sequential presentation. For instance, two signals presented in phase but to different locations will result in the percept of a single stimulus in-between (e.g., Sherrick, Cholewiak, & Collins, 1990), and two points separated in time and location may result in a motion percept from the first to the second points (Kirman, 1974; Sherrick, 1968).

5. *Presenting complex continuous signals*. The tactile channel may not be very good in processing complex continuous signals (i.e., using a tactile display as tracking display), at least compared to other sensory channels. There are indications that tracking error with a tactile display is up to four times the error with a visual display (e.g., Hahn, 1965; Triggs, Lewison, & Sanneman, 1974). Part of this difference may be caused by inherent differences between the employed displays (e.g., no preview with tactile displays). No recent results with more advanced tactile displays are available yet.

We designed two variants of the tactile display. The simple display variant presents information on the direction of the drift (error) only. The complex variant presents error information as well as additional information on the current direction of motion.

Simple version.
The simple version only presents information on the direction of the set point (i.e., the origin in 3D space). This is implemented by activating single points of the display. Two analogies can be used here. The first is that the activated element indicates the desired direction (as would be done with indicating the desired route or the next waypoint). The second analogy is that the element indicates the direction of the drift, i.e., liking bumping into a virtual wall. We chose the first coding principle, for of two reasons. The first is the resemblance with the waypoint analogy; a consistent coding in this case would be that the vibration indicates the desired direction. Second, this coding unambiguously indicates the optimal direction of motion, while the virtual wall analogy indicates the direction to avoid, which leaves the pilot with the choice to determine the optimal steering action (many motion directions will free the pilot from the wall, of which the 180 degrees opposite (mirrored through the body midline?) is the optimum). By using a belt around the torso, we integrated the two horizontal degrees of freedom into one direction in the horizontal plane. Van Erp (2001a) already showed that such an integration leads to a robust and accurate percept of direction. The desired motion in the vertical direction was indicated by activating elements under the thighs and on the shoulders (for set point below and above current altitude, respectively).

Complex version.
In version 2, the momentaneous motion direction is added to the direction of the set point. Motion was not presented by single points, but by a (apparent) motion across the torso. This was implemented in the horizontal plane by two points that move symmetrically towards the direction of motion (e.g., when moving forward, the points would start at the left and right side and move forward to meet right in front; when moving to the left, the points would start on the spine and on the navel and move simultaneously to the left. Combined with the coding of the desired direction, moving in the right direction means that the motion points end in the point that indicates the direction. As long as these points don't coincide, the pilot moves in the wrong direction.

Methods

Participants
Twelve participants flew in a rotary wing simulator. They were students of the Royal Dutch Airlines Flight Academy (KLS). Their mean age was 22.4 years, their mean flying experience was 160 hour (range 110 – 200 hours). They had no experience with tactile displays and the TNO flight simulator. They had no particular experience with helicopter hovering. They were paid the equivalent of Euro 50 for their participation.

Figure 1. Example of a simulator image in the 'rich' environment.

Task and simulator
The participant flew scenarios consisting of three phases: hovering, low level flight, and hovering again. This paper reports only on the two hovering phases. In these phases, the instruction was to hold a specific position in 3D space. The two hovering phases were at different locations in the database: one location was a visually rich environment (including unique objects and objects taller than the hovering altitude; see Figure 1), the other environment was sparse (only fields and woodland). Each phase consisted of an initial stage (30 s) and a recording stage (120 s without a secondary task, 120 s with a secondary task, see below). At the beginning of each hovering phase, the helicopter was at ground level. The instructed altitude was 15 m. During the initial stage, the altitude error was presented as a head-up display. Directly after the 30 s initial stage, the altitude error was switched off and the recording stage started. The altitude set point for the recording phase was the instructed altitude (15 m), the horizontal set point was the horizontal position at the onset of the recording phase.

The flight simulator consisted of a helicopter mock-up with full controls and a cylindrical dome measuring 140 by 40 degrees of visual angle. The helicopter model was a simplified, linearized helicopter model, fine-tuned by an experienced Couger pilot. Three Evans & Sutherland® Simfusion image generators generated the visuals. NVG vision was simulated by the image generators (in hardware). In the NVG conditions, the participant wore field size restricting goggles (field size 40 degrees, 100% overlap, no optics).

During the second half of each hovering phase, the participant performed a secondary task: the auditory continuous memory task (CMT). The CMT consists of series of spoken letters of the Dutch alphabet and was presented through headphones. Each time the subject detected a target letter a button had to be pressed, that was positioned on the stick near the thumb. There were four target letters (A, B, C and D). The letters had also to be counted in separate tallies. The button had to be pressed twice when a target letter was presented for the second time. If this response was correct, the subject heard the word "correct". When the subject pressed the button at an incorrect moment or when an omission was made, the word "wrong" was presented in the headphone. After the feedback ("correct" or "wrong") the tally for the last letter had to be set to zero. The letter's E, G, H, P, T, V and W were not used because the sound of these letters could be confused with the target letters. Target letters were never presented in succession. Thirty percent of the letters were targets. The duration of the CMT was two minutes (see Veltman & Gaillard (1996, 1998) for further details).

Tactile display

The tactile display was developed by TNO Human Factors. The display consisted of 64 elements. These were custom build and based on DC motors that were housed in a PVC contactor with a contact area of 1.5 by 2.0 cm. The elements vibrated with a frequency of 160 Hz. The elements were build-in in a stretch fleece vest. The elements were organized in 12 columns (exactly at 1, 2,...,12 'o clock), and five rows (equally distributed between the navel and the nipples). The four remaining elements were attached to both shoulders and under both thighs. The direction of the origin was indicated by pulsing elements. The pulsing rhythm was dependent on the error. For errors smaller than 1 m no signal was given, for errors between 1 and 5 m the rhythm was 100 ms on - 200 ms off, for errors larger than 5 m the rhythm was 50 ms on – 100 ms off. The motion direction signal consisted of five (discrete) steps in the direction of motion. The onset of the next element coincided with the offset of the former element with a pause between the last burst and the onset of a new series. Burst duration and pause were speed dependent 0 ms (speed lower than 0.1 m/s), 100 ms burst and 200 ms pause (speed between 0.1 and 1 m/s), and 50 ms and 100 ms pause (speed higher than 1 m/s).

Performance measures and data analyses

For each of the phases, we calculated the position error, separately for the horizontal direction and the vertical direction. Performance on the CMT was measured by the Reaction Time to the double clicks and the percentage correct. Finally, participants indicated their subjective workload after each run on the Rating Scale Mental Effort (Zijlstra & Van Doorn, 1985).

Each performance measure was analyzed by a repeated measures analysis of variance: Vision (full vision / NVG vision) × Tactile display (none / simple version / complex version) × Environment (rich / sparse) × CMT phase (before CMT / during CMT).

Procedure

The participants came for a full day. They came in pairs and took turns after each session. After arrival they were introduced to the general procedures of the experiment. During the morning they were trained on the task and the simulation environment. This training consisted of four 20-minutes sessions for each participant, with full and NVG vision and with and without CMT. During the afternoon, each participant flew three blocks of two runs. Each run took 13 minutes net flying time.

Results

Hover performance

We discuss the results per performance measure. The position error in the horizontal direction showed several main effects and two-way interactions, see Table 1. The main effects of Vision, Environment, and CMT showed that performance degrades with night vision, a sparse environment and during the CMT phase, respectively (the means can be deducted from Figures 2-4). The interactions between these independent variables showed that the effects strengthen each other. Of primary interest however, were the main effect and interactions with the tactile display. The main effect showed performance improvements with the tactile

displays: The simple variant reduces the error with 27%, the complex variant with 25%, compared to the no-suit condition. The interactions are depicted in Figures 2-4. The non-significant interaction between Vision and Tactile suit (Figure 2) showed that both tactile suits reduced the position error considerably compared to the no-suit condition, not only in the night vision condition (mean reduction 22%), but also in the full vision condition (mean reduction 32%). The interaction between Environment and Tactile suit (Figure 3) showed that the error reduction of the tactile suits is larger in the sparse environment (28%) than in the rich environments (20%). Finally, the interaction between CMT and Tactile (Figure 4) showed that there is no effect of the tactile suits in the phase before the CMT task, and a large error reduction (35%) during the CMT phase.

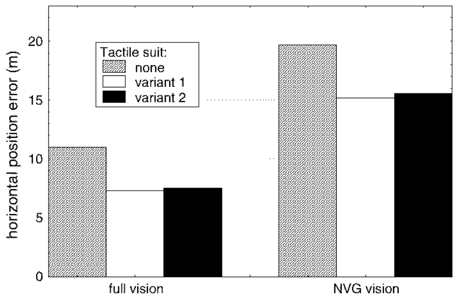

Figure 2. Horizontal error as function of visual and tactile display condition.

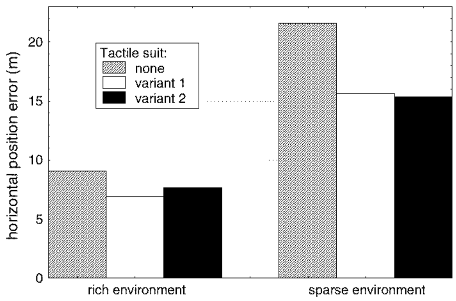

Figure 3. Significant interaction of environment and tactile display on the horizontal error.

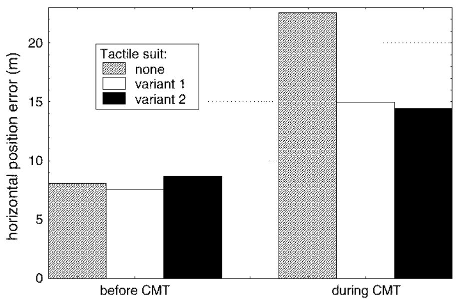

Figure 4. Significant interaction of the presence of the secondary task and tactile display on the horizontal error.

Table 1. ANOVA results on the horizontal position error (higher order effects omitted).

Effect	df	F-value	p-level
Vision (V)	1, 11	93.35	.001
Tactile (T)	2, 22	5.88	.009
Environment (E)	1, 11	59.28	.001
CMT (C)	1, 11	57.34	.001
V × T	2, 22	104.92	.95
V × E	1, 11	93.51	.005
T × E	2, 22	35.04	.025
V × C	1, 11	53.27	.001
T × C	2, 22	45.67	.001
E × C	1, 11	120.20	.001

An overview of the ANOVA results on the vertical error is presented in Table 2. The main effects of Environment and CMT showed degraded performance in the sparse environment compared to the rich environment (means 2.18 and 0.77 m), and during the phase with the CMT compared to without the CMT (means 1.78 and 1.17 m), respectively. The main effect of Tactile suit showed an error reduction of 55% for the simple variant and 47% for the complex variant, compared to performance without a tactile suit. The non-significant interaction of Vision and Tactile suit indicated an error reduction both with NVG vision and full vision (see Figure 5). The interaction of Tactile suit and CMT is depicted in Figure 6. This interaction showed that the error reduction of the tactile suits is larger in the CMT phase than in the phase before the CMT.

Table 2. ANOVA results on the vertical error (higher order effects omitted).

Effect	df	F-value	p-level
Vision (V)	1, 11	2.77	.12
Tactile (T)	2, 22	16.06	.001
Environment (E)	1, 11	17.45	.002
CMT (C)	1, 11	5.52	.039
V × T	2, 22	1.58	.23
V × E	1, 11	2.90	.12
T × E	2, 22	1.93	.17
V × C	1, 11	1.79	.21
T × C	2, 22	3.66	.043
E × C	1, 11	3.04	.11

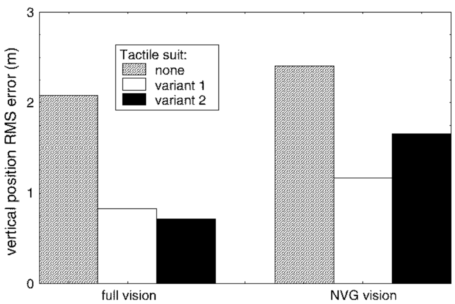

Figure 5. Vertical error as function of vision and tactile display.

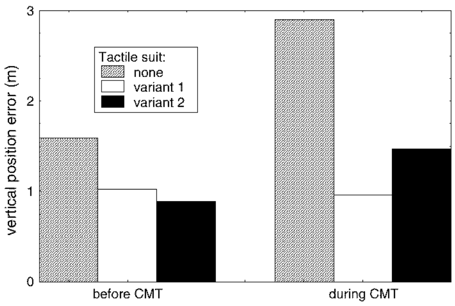

Figure 6. Significant interaction of the presence of the secondary task and tactile display on the vertical error.

Performance on the secondary (CMT) task
There were no effects on either the reaction time (mean 900 ms) or the percentage correct (mean 90%).

Mental effort rating
Two main effects on the mental effort rating were significant: Vision ($F(1, 11) = 7.18$, $p = .021$) and CMT ($F(1, 11) = 14.40$, $p = .003$). The means showed a higher mental effort with night vision compared to full vision (means 57.8 and 48.4, respectively) and higher mental effort in the CMT phase compared to the phase before the CMT (means 56.9 and 49.3, respectively).

Discussion

The first observation is that both tactile display variants improve the performance on the horizontal as well as the vertical dimension. Compared to the no-suit condition, the simple variant reduces the horizontal error with 27% and the vertical error by 56%. For the complex variant, these reductions are 25% and 47%, respectively. The various interactions provide further insight into the effects of the tactile displays. We will discuss them in relation to our objectives and hypotheses. The first objective of the present study was to investigate whether a tactile display can help to compensate for the degraded visual information when flying with Night Vision Goggles. To our surprise, the tactile displays result in large performance improvements in both the night vision and the full vision conditions. The latter is not according to our hypothesis. It shows that the positive effect of the tactile displays is so strong that it can even support the pilot under full vision condition. Image quality was also varied by using a rich and a sparse environment. The positive effect of the tactile displays is present in both environments, but indeed larger on the horizontal error in the sparse environment. The third manipulation was the presence of a secondary task (Continuous Memory Task, CMT). For both the horizontal and vertical error, there is a significant interaction between the tactile display and the presence of the CMT. This confirms our hypothesis that the presence of a tactile display reduces the negative effect of adding a secondary task on performance. Without a tactile display, adding a cognitive task results in a factor 2.8 increase of the horizontal error and a factor 1.8 of the vertical error. However, with a tactile display, these factors are only 1.8 and 1.3, respectively. This indicates that a tactile display (or actually adding information) reduces the negative effects of increased cognitive load. Furthermore, although the tactile display increases the amount of information to be processed, the mental effort ratings show that this is not at the cost of higher mental effort. These results confirm the claim that a tactile display presents spatial information intuitively and can be used with low level processing.

The results also show that the differences between the simple and the complex variant are small. Both displays show the same effect on the horizontal error. On the vertical error, the complex variant shows the tendency to be somewhat less effective than the simple variant. Several aspects are relevant here: (1) the usefulness of the extra information that the complex variant presents (i.e., information on the current motion direction) (2) the interaction between tactile signals, which we call tactile clutter and (3) the extent to which the presentation or coding is intuitive. Of course, the first factor and the second and third are like the flipsides of a coin. When the benefit of the additional information is smaller than the costs involved, the complex variant may lead to worse performance than the simple variant. We hypothesize that the critical factor in the present design is tactile clutter. Although the skin is able to process large amounts of (abstract) information -people can read Braille with their fingers- the complex variant may have suffered from the interaction between signals. Adding a moving stimulus may result in a cacophony of tactile stimuli that may result in unpredictable spatio-temporal interactions. Furthermore, the resulting tactile clutter may degrade the intuitiveness of the signals; i.e., some form of processing is required to separate the different components.

This latter is confirmed by the data of the interaction between tactile display and CMT task: with the secondary task present, performance with the simple variant is better than with the complex variant. This indicates that the complex variant has a claim on some form of the higher order processing resources needed in the secondary task. The concept of tactile clutter and the intuitiveness of the coding are both areas that need further research.

Conclusions

This simulator study proves the potential of intuitive tactile torso displays in reducing drift. The display is so effective that it not only results in performance improvement under reduced visual condition, but also under full vision conditions. Also, the presence of a tactile display reduces the performance degradation caused by a secondary (cognitive memory) task. There is no effect of the tactile display on the subjective mental effort rating.

Moreover, the results prove that tactile displays can be applied in fast man-in-the-loop tasks. Finally, advanced tactile displays that are able to present more complex stimuli open up new possibilities of information presentation. This can possibly improve performance, but may also introduce tactile clutter.

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